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YOUR REF
OUR REF 1835/RMC

22nd July, 1966.

The Secretary,
Scottish Development Department,
St. Andrew's House,
Edinburgh.

The Secretary,
Water Resources Board,
Reading Bridge Houss,
Reading.

Dear Sirs,

<u>Solway Barrage</u>
<u>Water Supply Scheme</u>
<u>Desk Study</u>

By letter dated 1st November 1965 we were appointed jointly hy the Ssecretary of Siate for Scotland and the Water Resources Board to examine, on a preliminary basis, the feasibility of constructing a barrags to develop ths Solway Firth as a source of water supply, our specific terms of reference heing to undertake a "desk study" hased upon such documentary and other records as are available in order to determine:-

I The quantity of water which can be mads availahle,

II The problems associated with making that water potable, and

III Ths prohable cost of making that quantity of potable water availabls.

In the accompanying report we describe the course of our investigations and, with the aid of the appended tables, diagrams and plans, present our findings on each of the several study sections into which the main heads of our terms of reference have been subdivided.

The present study is of course merely a first step towards a full feasibility study which would be based on information obtained from detailed site surveys, exploratory borings and model investigations. Meantime, in the absence of such precise data, some of our conclusions are necessarily tentative. With that overriding qualification we would summarise the findings of the desk study as under:-

1. A barrage across the Solway is considered to be practicable and to have potentialities justifying the institution of a comprehensive feasibility study

2. At the most favourable barrage site the size of reservoir which can be formed to provide balancing storage is small in relation to the run-off from the extensive catchment. This gives rise to problems of flood control, siltation and variations in water quality all of which could, however, be overcome by reasonable means. As a result a practical scheme could be developed to produce large quantities of water at low cost.

3. In a first stage of development a supply of 380 million gallons per day could be made available. This could be increased in a second stage to 465 mgd and in an ultimate third stage to 585 mgd.

4. Water of good potable standard could be produced by means of filtration plant of the type normally used to treat impounded surface waters. Because of the large volume of supply, the cost of the treatment provisions would represent the greater part - up to 75% - of the total capital expenditure involved in the scheme.

5. The first stage of development for 380 mgd would entail capital expenditure of £29 million, of which £6 million would be in respect of the barrage structure. The overall cost would be £34 million for the second stage yield of 465 mgd and £42 million for the ultimate yield of 585 mgd.

6. If the capacity of the draw-off and treatment works were limited in the first instance to 100 mgd, the initial capital cost would be £13 million.

7. Taking account of loan charges and running costs, and basing on the full yields, the unit costs in pence per 1000 gallons of treated water provided in tanks 35 feet above sea level would be 5.29d. for the first stage, 5.65d. for the second, and 5.00d. for the third. The unit cost of the first 100 mgd of treated water would be 8.35d. per 1000 gallons.

8. Untreated water could be delivered to tanks 50 feet above sea level at unit costs of 1.62d. per 1000 gallons for a supply of 380 mgd and of 4.40d. per 1000 gallons for the first 100 mgd.

9. Rockcliffe and Burgh Marshes at the head of the firth are the main areas of land bordering the reservoir where present use would be directly affected, particularly by the works envisaged in the second and third stages of development.

10. The important river and coastal fisheries of the Solway would probably be adversely affected for a period following the construction of a barrage. It would nevertheless appear that with the provision of facilities to ensure the passage of migratory fish through the barrage, any long term effects would not be serious.

11. The barrage, in addition to its primary function of creating a source of water supply, could convey certain incidental benefits. The freshwater lake with an area of some 16 square miles could enhance the amenities of the district and give scope for fishing, sailing and other recreational activities. The barrage itself would provide the opportunity for improving road communication between Scotland and North-West England. In carrying out dredging to counteract siltation in the reservoir, certain areas of marsh and foreshore could in time be reclaimed and turned to agricultural or other use.

12. As regards the time required for development, if allowance be made for the feasibility study, for the negotiation of the administrative and financial arrangements, for the acquisition of the necessary statutory powers and for the design and construction of the works, it is apparent that an overall period of 11 to 12 years would be taken up in bringing the scheme to fruition.

The considerations leading to these conclusions are explained in the report, which in the technical sense is based on calculations worked out in British units as expressed in the foregoing summary. To accord with current official policy we have embodied in the report the equivalent values of all figures in metric units, generally in parenthesis. A list of the symbols and abbreviations employed is given after the index which prefaces the report.

Yours faithfully,

Babtie Shaw & Morton

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SYMBOLS AND ABBREVIATIONS

British units

mgd	-	millions of gallons per day
cusecs	-	cubic feet per second
a.d.f.	-	average daily flow

Metric units

mm	-	millimetre
m	-	metre
km	-	kilometre
km^2	-	square kilometre
m^3	-	cubic metre
m^3/s	-	cubic metres per second
$l/s\ km^2$	-	litres per second per square kilometre
mg/l	-	milligrams per litre
kg	-	kilogram

SOLWAY BARRAGE

WATER SUPPLY SCHEME

DESK STUDY

REPORT hy
Bahtie, Shaw & Morton
Consulting Civil Engineers

Introduction

As a source of water supply the Solway Firth has potential yields extending over a considerable range, depending on the particular site selected for a harrage. As one proceeds seawards down the firth the extent of the contributory catchment increases substantially, as also does the storage capacity of the tidal basin as the estuary hecomes wider and deeper. There is thus a progressive rise in the yield which may be harnessed, accompanied by a progressive rise in the scale and coet of the harrage works required.

Early in our investigations we made an approximate assessment of the potentialities of five possihle barrage locations within that part of the firth extending westwards from an inner line hetween Seafield and Bowness to an outer line between Southerness Point and Dubmill Point, as shown on Plan No. 1. This hroad comparison indicated that the scheme involving the least capital expenditure and producing the cheapest water was that hased on the innermost line. Altbough the potential yield here was the lowest of all the schemes considered, it was regarded as more than sufficient to cover the foreseeable needs of the supply areas lying within reasonable range of the source.

In these circumstances our suhsequent studies were concentrated on this particular harrage location, which is across the narrowest neck of the firth at the entrance to what may he termed the inner estuary, on a line coinciding witb the site of the railway viaduct which at one time crossed the Solway. Some further ohservations on the other sites considered are included towards the end of the report. Meantime the discussions and figures which follow relate to the proposal for a harrage on the Seafield-Bowness or "viaduct" line.

I. WATER QUANTITY AND YIELD

The catchment area draining to the barrage site is delineated on Plan No. 1. It extends to 1455 square miles (3770 km^2) or just over 930 000 acres, of which 75% is in England where the watershed embraces parts of the Lake District and the Northern Pennines, with the balance of 25% in Scotland whers the watershed embraces part of the Southern Uplands. There are two main rivers, the Eden and the Border Esk which, with their tributaries, drain areas of 917 square miles (2375 km^2) and 453 square miles (1175 km^2). The remaining 85 square miles (220 km^2) are drained by the River Sark, the Kirtle Water and other smaller streams.

(a) The amount and variability of run-off

The average rainfall for the standard psriod 1916 - 1950, for which the isohyets are shown on Plan No. 1, ranges from fully 100 inches (2540 mm) per annum on the Lake District peaks of Helvellyn and Skiddaw, and from fully 70 inches (1778 mm) per annum on the higher parts of the Scottish Southern Uplands, down to 32.5 inches (825 mm) per annum in the lower valleys and over the firth itself. The long-term average for the catchment as a whole is estimated at 49 inches (1245 mm) per annum. This may vary between extremes of about 30 inches (762 mm) in the driest year to perhaps 80 inches (2032 mm) in the wettest.

Published data based on researches into the losses due to svaporation and transpiration throughout the British Isles show values for such losses of 14 inches (356 mm) per annum for the northern part and 16 inches (406 mm) per annum for the southern part of the Solway catchment. For present purposes we have considered it prudent to adopt the higher figure of loss as applying to the whole area. This means that in a year of average rainfall the net run-off is 33 inches (838 mm), which represents an average rate of flow from the whole catchment area of 1900 mgd (100 m^3/s).

Dry weather flows

In estimating the lowest flows liable to occur in a prolonged period of drought, we have based on such information as is available from the river gauging stations in or near the area. Within the area there are two stations on the Esk at Canonbie and Netherby and one on ths Eden at Warwick Bridge for which records since 1962, 1963 and 1964 respectively are available. The observations relating to these rivers therefore cover relatively short periods. Continuous observations of longer duration are available for a gauging station on the River Nith established in its present form at Friar's Carse in 1957. Although the Nith lies 20 miles (32 km) to the west of the catchment under review, the gauging records from it are of particular interest in that they cover the extreme dry spell which occurred with such widespread effect in the summer of 1959.

The flows recorded on the Nith in 1959 during a period of virtual drought lasting for 72 consecutive days have been adjusted to take account of differences in the natural features of the respective catchments, and to allow for the possibility of even more testing conditions occurring in future. On this basis we estimate that from the whole catchment area draining to the barrage site the minimum dry weather flows may be of the following order:-

		mgd	m^3/s
Over one day	.....	140	7.4
Over 7 consecutive days	.....	145	7.6
Over 30 consecutive days	.....	160	8.4
Over 72 consecutive days	.....	215	11.3

Flood flows

Information from the river ganging statione referred to also provides guidance as to the possible scale of the peak flood run-off in times of storm. On the Esk a flow of 40 000 cusecs (1130 m^3/s) from an area of 208 000 acres (840 km^2) has been recorded, giving a unit rate of run-off of 192 cusecs per 1000 acres (1350 $l/s\ km^2$). From an area of 197 000 acres (797 km^2) on the Nith a flood of 45 000 cusecs (1275 m^3/s) has been recorded, giving a unit rate of 228 cusecs per 1000 acres (1600 $l/s\ km^2$), while there are also records of five other floode on thie river in the range from 150 to 180 cusecs per 1000 acres (1050 to 1260 $l/e\ km^2$).

Over an area as extensive as that draining to the barrage site, stretching 70 miles (113 km) from north to south, 45 miles (72 km) from east to west, embracing some 930 000 acres (3770 km^2) and containing two main river basins of differing topography and exposure, there will in the course of any one storm be considerable variations with time and place in the incidence and intensity of the rainfall, resulting in an average unit rate of flood run-off from the catchment as a whole appreciably less than that applying to its individual upland sections. The published analytical studies of flood records in the British Isles indicate that for an area of this size the run-off causing a flood of the "normal maximum" category could average just under 100 cusecs per 1000 acres (700 $l/s\ km^2$), giving a total flood flow of 90 000 cusecs (2550 m^3/s) and that, under possible exceptional conditions, the run-off could average 130 cusecs per 1000 acres (910 $l/s\ km^2$) giving a total peak flood flow of 120 000 cueece (3400 m^3/s).

Summary

To summarise this section, our findings are that over the long term the average daily flow from the catchment is at the rate of 1900 mgd (100 m^3/s) with fluctuatione above and below this figure according to the vagaries of the weather from a maximum of 120 000 cusecs (3400 m^3/s) to a minimum of 140 mgd (7.4 m^3/s) showing an overall variability ratio of 465 to 1.

(b) The storage which can be provided

Up to high water mark the inner estuary covers an area of 16.2 square miles (42 km^2) which is 1.1% of the catchment. Except for the meandering cbannels of the Rivers Eden and Esk, the area dries out completely at low tide.

By the construction of a barrage to exclude the sea, this tidal basin could be converted into a fresh water reservoir, with a storage capacity dependent on the height to which water was impounded. Determination of the optimum impounding level involves a number of considerations arising from the existing tidal, physical and other cbaracteristics of the firth.

Tidal data

To obtain information ahout tidal levels, we carried out a series of simultaneous ohservations at four selected stations over two complete spring tide and neap tide cycles. Tbe observation points are shown on Plan No. 2 and the results plotted ae tidal curves are reproduced in Diagram No. 1. On the basis of this information estimations bave been made for eacb of the four stations of the range of tidal levels between the lowest and the higbest astronomical tide, between mean low water and mean high water springs, and between mean low water and mean high water neaps. These figures related to Ordnance Datum (Newlyn) are set out in Table No. 1.

As might he expected in an estuary of this shape, there is for any one tide a progressive rise in the high water level towards the head of the firth where, in the case of the highest astronomical tide, the water level comee up 2.8 feet (0.85 m) higber than at Silloth, about 15 miles (24 km) down-firth. The introduction of a barrage would prohably affect the preeent amplitude and timing of the tides to seaward of the site, to an extent which could hest be determined beforehand by tidal model studies. Under existing conditions at tbe barrage site it ie estimated that mean higb water is + 8.8 feet (2.68 m) O.D. at neaps and + 16.9 feet (5.15 m) O.D. at springs, rising to + 20.2 feet (6.16 m) O.D. in the caee of tbe highest astronomical tide. Above these predicted levels the tidal surges liable to occur when strong west or south-west winds are accompanied by low atmospheric pressure could raise the sea water surface some 2 to 3 feet (0.6 to 0.9 m). For a probable frequency of occurrence of once in 200 years, the extreme high tide level at the barrage site is calculated to he + 22.4 feet (6.83 m) O.D.

These figures make no allowance for wave heigbts or for the continuing rise in mean sea level which is taking place around these shores at an estimated rate of 1 foot (0.3 m) per century. Tbese are factors to be taken into account in the design of the barrage works.

Topography of reservoir area

On the tidal basin whicb would be enclosed by a barrage, the ground hehind the shoreline on the northern or Scottish side rises in the main fairly steeply above high water mark, so that the impounding level adopted would not, within limite, be critical so far as affecting marginal lands and properties. The same appliee for part of the way on the English side, along the coastline between

Bowness and Drumburgh. At the head of the basin, however, there are extensive flat areas where the surface level lies between + 18 and + 19 feet (5.5 to 5.8 m) O.D. These comprise Rockcliffe Marsh, occupying the peninsular area between the mouths of the Esk and the Eden, and Burgh Marsh, lying between Burgh-by-Sands and the coast, as outlined on Plan No. 2.

These areas are subject to complete submergence by the tides for a few hours during several days on two or three occasions per annum, as also are stretches of the unclassified road running from Burgh-by-Sands via Drumburgh and Port Carlisle to Bowness, on which notices are posted warning of possible tidal flooding to depths of 2 feet (0.6 m) or more. Behind Rockcliffe Marsh the arable lands are protected by flood banks built up to about + 26 feet (8.0 m) O.D., through which there are drainage culverts fitted with tidal flaps at invert levels of + 15 to + 16 feet (4.6 to 4.9 m) O.D.

Rockcliffe and Burgh Marshes, extending in all to fully 3000 acres (12 km^2) are of importance not only because of their considerable value as grazings for cattle and sheep, but also because they have been scheduled by Nature Conservancy as "Sites of Special Scientific Interest" through being salt marshes supporting flora and fauna peculiar to such areas. They are the habitat of numerous species of sea-bird and wildfowl and, in particular, are the wintering quarters of many thousands of barnacle, pink-footed and greylag geese which migrate yearly from Greenland, Spitzbergen and Iceland.

Initial impounding level

If it proved desirable at least in the first instance to preserve these marshes from inundation, the highest practical level of impoundment in the reservoir would be restricted to +15 feet (4.57 m) O.D. This is some 3 feet (0.9 m) below the present tidal level here at mean high water springs, and possibly 6 feet to 9 feet (1.8 to 2.8 m) below the extreme tidal levels to which the area is at present subject. With a barrage controlling the reservoir to a normal top water level of + 15 feet (4.57 m) O.D., the periodic flooding now affecting the coastal road to the west of Burgh-by-Sands would be virtually eliminated, while the occasional flooding along the lower reaches of the Esk and the Eden, in so far as this is due to river spates being coincident with the higher tide levels, would be substantially alleviated.

Flood control

A top water level of + 15 feet (4.57 m) O.D. in the reservoir would be lower than the level of the sea on the other side of the barrage for a few hours during the peaks of the higher tide cycles, up to a possible maximum of fully 7 feet (2.1 m). On such occasions the discharge of water seawards by gravity would not of course be possible until the tide receded sufficiently to provide the necessary differential head. To cover the case of a high flood run-off coinciding with a high tide, it is accordingly necessary to provide flood accommodation in the reservoir. Flood control is of particular significance in this case because the area of the reservoir is so small relative to that of the contributory catchment, as is emphasised by the fact that 1 inch (25.4 mm) of run-off from the catchment is equivalent to 8.5 feet (2.6 m) over the reservoir surface at the + 15 feet (4.57 m) O.D. level.

In order to limit the possihle rise of the reservoir water level at times of heavy run-off, we suggest that it he temporarily lowered in anticipation of flood conditions, hy perhaps 3 feet (0.9 m) to give extra capacity for storing flood waters until the tidal conditions permitted their discharge to sea through the spillway provisions at the harrage. At times of medium or high inflow a temporary reduction of storage for this purpose would not of course reduce the effective yield of the reservoir.

We therefore visualise a reservoir with two "top water" levels, one at + 15 feet (4.57 m) O.D. for dry weather conditions and the second at say + 12 feet (3.66 m) O.D. for wet weather conditions. Control would he hy means of the spillway provisions at the harrage, correlated to the prevailing or forecast weather and tidal conditions and so operated that, around a pre-determined datum of say average run-off, the reservoir level would he maintained to + 15 feet (4.57 m) O.D. on a falling inflow, and lowered in stages to + 12 feet (3.66 m) O.D. on a rising inflow. As the timing and height of extreme tides are largely predictahle, and as observations of rainfall and river flows would give advance warning of impending floods, this method of control should prove reasonahly straightforward in practice, subject to there heing adequate spillway capacity at the harrage to provide during the ehh tide for the release of the stored flood waters as well as for the passage of a continuing spate.

The chances of an exceptional flood of 120 000 cusecs (3400 m^3/s)coinciding not only with the highest astronomical tide but also with the maximum tidal surge are extremely remote. Even if this did occur, the maximum water level in the reservoir could, hy the provisions and procedure outlined, he kept well helow the extreme tidal flood levels to which the area is now suhject. Normal maximum floods of 90 000 cusecs (2550 m^3/s) occurring simultaneously with extreme tides might result in the hrief inundation of the marshes and of the Burgh-by-Sands road perhaps once or twice per century, instead of two or three times per annum as at present.

Reservoir capacity

To determine the capacity of the tidal hasin above the harrage line we have carried out instrumental surveys, the results of which are plotted as contours on Plan No. 3. From this information we have prepared the depth-capacity curve given on Diagram No. 2, which shows that between a top water level of + 15 feet (4.57 m) O.D. and a possihle lowest draw-down level of Ordnance Datum, the effective capacity availahle for use as halancing storage amounts to 20 000 million gallons (91 x $10^6 m^3$).

Movement of sea-hed material

The hed of the tidal hasin is covered hy extensive deposits of fine sand overlying a stratum of houlder clay. Considerable changes in the position and configuration of the sandhanks take place through hoth tidal and fluvial influences, especially in times of storm. Examination of early charts and maps of the Solway alongside recent plans and aerial photographs indicates the major extent of the changes liahle to occur in the disposition of the hanks and channels within the firth hoth in the short and the long term. This applies not only to the inner

estuary but also to the extensive sandbanks in the inter-tidal parts of the outer firth.

Throughout the area the sand is of the same fine consistency to a remarkably uniform degree, a typical analysis being:-

Particle Size	Proportion
0.25 to 0.125 mm	2%
0.125 to 0.0625 mm	70%
Under 0.0625 mm	28%

An average particle of 0.08 mm diameter has a settling velocity in still fresh water of 1 foot (0.3 m) per minute.

Previous studies of the movement of sea-bed material in the Solway Firth point to this sand having its origin in the Irish Sea, with only a small proportion contributed by the rivers. Within the estuary it is kept in suspension largely through wave action and is thus readily transported by the strong tidal streams which prevail especially on the flood tide.

A feature of the Solway is the tidal bore which appears on the flood of the higher spring tides and which is reputed to reach on occasion a height of 5 feet (1.5 m). We have observed it several times with a wave-front 2 feet (0.6 m) high travelling at a measured speed of 13 feet per second (4.0 m/s). On such occasions the sea water is highly turbid because of the heavy burden of sand in suspension.

Much of the sand carried up-firth on the flood tide is carried out again on the ebb, particularly when the water surface is whipped up by strong winds or when the somewhat slower tidal currents then prevailing are increased by flood flows from the rivers. During the dry summer of 1959 a number of new sandbanks were built up by sea action in several places, eventually to disappear with the coming of the winter spates.

In such changes the wind by its influence on wave production plays an important part, in which connection it may be noted that the Solway srea is seldom becalmed. In Table No. 2 we reproduce particulars of the wind directions and strengths recorded daily at Silloth Airfield over the eight years 1949-56. These show that winds from the south-west predominate and that on 50% of all occasions the wind force is between 4 and 5 on the Beaufort scale (15 to 21 miles or 24 to 34 kilometres per hour).

Whilst under existing conditions there is a large body of sand more or less continuously on the move up and down the firth, the long-term trend is one of gradual accretion in the areas of slacker water within the upper estuary. In the narrow neck at the barrage site sand deposition is slight but in the upper part of the proposed reservoir basin there are accumulations of sea-borne sand possibly amounting to 60 million cubic yards, taking up water storage capacity of 10 000 million gallons ($45.5 \times 10^6 m^3$). The presence of this sand makes much of the reservoir area very shallow. Below a top water level of + 15 feet (4.57 m) O.D. the average depth overall is 8.5 feet (2.6 m) from a maximum of 29 feet (8.9 m) at

the barrage tapering off along the length of the reservoir to zero on the sandbanks some 6 miles (9.7 km) to the east. Here at the upper end of the basin about 20% of the reservoir area is less than 3 feet (0.9 m) deep, giving conditions conducive to the development of reed and weed growth and possibly also of algae, which if pronounced could necessitate special control and treatment measures.

Siltation

A more serious problem likely to affect the reservoir is that of siltation from the inflowing rivers. At the higher ranges of flow the Rivers Eden and Esk carry heavy silt loads which, under present circumstances, remain largely in suspension until carried out to sea by the tide. A reservoir with a sustained water level will act as a settling basin resulting in the deposition of the heavier material perhaps as bars at the river mouths and of the lighter material beyond possibly as mud banks or flats.

Within the scope of this study it has not been possible to carry out a full investigation involving observations over a complete range of river flows and employing the special techniques necessary for the sampling of bed loads and suspended solids. Although the results of the few observations which have been made must therefore be regarded as first approximations, they are nevertheless indicative of the probable scale of the problem.

On the basis of the information meantime available we calculate that the quantity of silt entering the reservoir through erosion of the catchment will average 275 cubic yards per square mile (81 m^3/km^2) per annum or a total for the whole catchment of 400 000 cubic yards (305 000 m^3) per annum, the bulk being brought in during periods of high river flow. If this figure is reasonably estimated, the initial storage capacity of the reservoir would be reduced at the rate of 0.33% per annum, leading to the complete silting up of the whole reservoir basin within 300 years.

To bring this matter into perspective we would make two comments. Firstly, siltation of the order indicated represents the denudation of the catchment surface at the rate of one-third of an inch (8.5 mm) per century. Secondly, siltation is of real significance here only because of the small size of the reservoir basin relative to the rate of run-off from the extensive catchment area. In the normal run of impounding schemes it is not unusual to provide balancing storage sufficient to harness the run-off deriving from up to 80% of the average rainfall. Had it been practicable to adopt that basis for the Solway, the reservoir would have been 13 times the size with a silting-up period of 4000 years, which would have reduced the problem to negligible proportions.

Dredging and reclamation

Loss of storage capacity through siltation would of course reduce the effective yield, and with a future growth of demands on the source there would come a time when maintenance dredging would have to be undertaken. This could probably best be done by means of a vessel of the cutter-suction type, with the dredged material pumped through a floating pipeline to the shore and thence through an overland pipeline, with intermediate boosters as necessary, to the selected disposal area. With such an installation in place, it would be desirable to make the

fullest possihle use of its output capacity and it could thus hecome economic to undertake not only "maintenance" dredging but also "improvement" dredging aimed at the removal of the sand deposits already within the reservoir hasin.

An area which suggests itself as a spoil ground for the dredged material is the estuary of the Rivers Wampool and Waver, shown on Plan No. 2, to which the pipeline approach could he by way of the disused railway between Drumhurgh and Kirkbride. Apart from the contiguous marshes of fully 2000 acres (8 km^2), there is a tidal area here of nearly 3000 acres (12 km^2) which could over a period be reclaimed and, with appropriate surface treatment, put to agricultural, forestry or other use.

Removal of the existing sand deposits from the reservoir would materially improve conditions from the water supply standpoint hy eliminating the greater part of the shallow areas at the upper end of the basin, while it would also appreciably increase the effective yield of the source by raising the volume of balancing storage by 50% to a figure of some 30 000 million gallons (136x $10^6 m^3$).

Ultimate impounding level

Looking even farther ahead, if there were justification because of rising demands for the provision of still more water, this could be achieved by raising the impounding level to say + 21 feet (6.40 m) O.D., which is still some 2 to 3 feet (0.6 to 0.9 m) below the extreme tidal level to which the basin is at present occasionally suhject. This would increase the total effective storage to 48 000 million gallons (218 x $10^6 m^3$) and would not involve any modification of the barrage, since the height of that structure is dictated by conditions on the seaward side. Moreover, by impounding in this way to a level above the normal range of the tides the need for special flood control procedure would he removed except for the most extreme conditions. It would however be necessary to provide a number of small pumping stations to take the surface water drainage from several areas of low-lying farmland around the fringes of the reservoir, as shown on Plan No. 2, and also to raise or protect the low parts of the road from Burgh-by-Sands to Drumburgh and Bowness, where a few properties would be affected. The cost of such measures would be small relative to the value of the additional yield furnished by the reservoir.

The ultimate raising of the impounding level to + 21 feet (6.40 m) O.D. would of course mean the end of Rockcliffe Marsh and Burgh Marsh. Long before then these areas would have ceased to be "salt" marshes although to what extent, if any, this change would have affected their use as grazings or as havens for wildfowl is a matter of conjecture. If the raising of the impounding level to + 21 feet (6.40 m) O.D. were accepted in principle as an ultimate development, then at the stage when improvement dredging was carried out there would be a case for using the immediately adjacent Rockcliffe and Burgh Marshes as the spoil grounds. Otherwise these areas would form extensive shallows at the hıgher water level.

Summary

In this section of the report we have digressed in places from the main theme to discuss matters which, though apparently incidental, nevertheless have a bearing on the prohlems associated with the provision and maintenance of reservoir storage,

as well as being relevant to other aspects of the study.

To sum up this section, we find that for an impounding level of + 15 feet (4.57 m) O.D. the storage would amount to 20 000 million gallons (91 x $10^6 m^3$), which would however be liable to be reduced by siltation at a possible rate of 0.33% per annum.

As a second stage of development, if improvement dredging were combined with maintenance dredging, the available storage could be increased possibly to 30 000 million gallons (136 x $10^6 m^3$).

In a third and final stage, the raising of the impounding level to + 21 feet (6.40 m) O.D. would increase the total storage to 48 000 million gallons (218 x $10^6 m^3$).

The timing of these possible stages of development could be geared to the growth of the demands on the source.

(c) The yield-storage relationship

The records available from the river gauging stations within the catchment do not extend over a sufficient number of years to be of direct service in assessments of yield relative to storage. Because of the limited capacity available in the reservoir the critical period as affecting yield is a dry spell of 4 to 6 months' duration, and in the circumstances we have used the Nith records for the dry summer of 1959 as a starting-off point.

By comparing such records of low flows as are available for the Eden and the Esk with the flows occurring in the Nith at the same times we have obtained a correlation between the run-offs from the two areas which has been adjusted to take account of the gauged and the ungauged portions of the Solway catchment.

From the records of three rain gauges situated within the area draining to the river gauging station on the Nith there have been abstracted the total rainfalls recorded in periods of two, three, four, five and six months up to the end of September for the year 1959 and for all other years between 1910 and 1965. With this information we have adjusted the cumulative discharge figures for the Nith from April to October 1959 to give the cumulative discharges from the Solway catchment that might be expected to occur in a year during which the total rainfalls over the two, three, four, five and six month periods to the end of September were the lowest that have been recorded over these same periods between 1910 and 1965.

From the adjusted cumulative discharges, after deducting evaporation losses from the reservoir for the particular monthly periods, we have prepared the synthetic cumulative curve shown on Diagram No. 3. Apart from the other allowances made the length of possible drought has been extended by two weeks as an additional margin of safety, and on this basis the diagram has been employed to determine the reliable yields for various amounts of storage.

By these means we have arrived at the yield-storage curve submitted as Diagram No. 4, showing the gross yields obtainable after making allowance for evaporation losses from the water surface of the reservoir.

For the three possible stages of development the respective yields would be:-

Storage			Gross Yield	
Million gallons	$m^3 \times 10^5$		mgd	m^3/s
20 000	91	....	415	21.8
30 000	136	....	500	26.3
48 000	218	....	620	32.6

(d) The net yield to supply

With the form of barrage proposed losses to seaward by percolation or seepage would be negligible, and the only deduction to be made from the gross yield is in respect of the discharges required to permit the passage of migratory fish.

As the harnessed yields represent only 20% to 30% of the average daily flow, for most of the time there would be ample water to serve fish passes or lifts, which would probably only be required to operate as such at particular states of the tide. Under extreme dry weather conditions the water devoted to the purpose would possibly be discharged at a rate of 75 mgd (3.95 m^3/s) for 6 hours per tide, giving an average flow of 35 mgd (1.84 m^3/s), on which basis the quantities of water which can be made available would be:-

Stage of development		Net Yield	
		mgd	m^3/s
I	....	380	20.0
II	....	465	24.5
III	....	585	30.8

Water use

These yields represent the "exportable" supplies which would be available for delivery to areas outwith the catchment or for use within the catchment on a wholly consumable basis as, for example, in cooling water make-up or in spray irrigation. In so far as part of the supply was used for domestic or other purposes locally and thereafter returned directly to the reservoir or to the rivers within the catchment, the net yields quoted would be correspondingly increased.

The effective yields would also be greater if the Solway source were utilised as a feeder for river regulation schemes, say to augment existing resources in North-East England, with supplies pumped via a pipeline and tunnel aqueduct extending to the east by south to deliver into the upper reaches of the River Tyne and perhaps also of the Rivers Wear and Tees. The possibilities in that direction open up a field of study beyond the scope of this remit.

As the balancing storage provided in the reservoir is all required to maintain the yield for water supply purposes in periods of drought, it would not be practicable to use the freshwater lake for the provision of cooling water to any major power station on a direct circulation basis. Part of the available yield could be devoted to such purpose if the heated water were returned to the seaward side of the barrage, while supplies of make-up water could be readily afforded to stations equipped with their own internal cooling circuits incorporating either wet or dry towers.

II. WATER QUALITY AND TREATMENT

(a) The quality of the water draining from the catchment

The population residing in the catchment is 151 000, of whom almost half are in the City of Carlisle. Here and at the other main centres of population the sewage treatment provisions are generally of a satisfactory standard. In the case of the smaller communities in some of the more rural parts of the area the sewage disposal arrangements are still rather limited but the amount of pollution so arising is small because of the high degree of dilution provided by the main watercourses.

The results of the routine sampling carried out by the River Authorities in the area confirm the generally clean condition of the rivers as regards freedom from contamination by sewage or trade waste effluents. We reproduce in Table No. 3 a batch of such analyses for the River Eden for different rates of flow, and in Table No. 4 the maximum and minimum results of similar sampling on the River Esk over a ten-year period.

Fuller analyses of the waters of the Eden and the Esk are set out in Table No. 5. These are based on samples which we took just after a fairly heavy flood when the river flows had fallen back to about 4 times average. At that time both rivers were still visibly silt-laden, although this condition is not correctly reflected in the analyses because the samples were drawn from the surface into narrow-necked containers. Using more appropriate equipment in tests made with reference to the siltation problem, there have been found on the Esk suspended solid concentrations of 63 mg/l at 4.7 times average flow, 683 mg/l at 15 times average flow and 1253 mg/l at 22 times average flow. Corresponding figures are not available for the River Eden but from a comparison of the two rivers under flood conditions we would expect these to show appreciably higher values.

As the water samples were drawn towards the end of a spate, the chemical analyses given in Table No. 5 may not be representative of normal conditions. We have noted that at times of lower flow the colour is markedly lower, spot samples taken on another occasion when the flows were about 1.5 times average giving colours as low as 5^{o} Hazen for the Eden and 20^{o} Hazen for the Esk. At such times also there is some increase in the total hardness, to figures of 102 mg/l on the Eden and 62 mg/l on the Esk.

The only independent flow of industrial effluent into the upper estuary is that discharging at the barrage site from the United Kingdom Atomic Energy Authority's establishment at Chapelcross, near Annan. The outfall pipe runs along the track of the old railway to an outlet at the end of the embankment which formed the northern abutment of the former viaduct, and could therefore be readily diverted to discharge on the seaward side of the barrage.

The radio-active substances now being discharged from Chapelcross, which are in practice substantially less in quantity than the limits prescribed in the official authorisation for the station, are apparently quickly dispersed by tidal influence without detectable effect. It further appears that virtually all the radio-active material found on the Solway foreshores emanates from the sea outfall of the Windscale plant on the Cumberland coast 40 miles (64 km) to the south. This is traceable along both coastlines up to the limits of tidal flow on the incomirg rivers, the dominant substance being Ruthenium 106, which has a half-life of one year. It is non-soluble in water but has an affinity for fine sand or silt particles. We are advised that no long-term effects would arise from any such material remaining in the reservoir basin after construction of a barrage.

(b) Residual contamination in the basin

Because of the small size of the reservoir relative to that of the catchment, the stored water would be subject to frequent and often rapid replacement at the rates of inflow occurring in wet weather. At average flow the whole reservoir contents would be displaced in 10 days while with a medium flood of ten times average flow the change-over period would be 24 hours. In such circumstances we consider that there would be a fairly rapid drop in the initial salinity of the impounded water and that the chloride content would fall to acceptable limits possibly within a matter of months, particularly if the natural processes were assisted by a series of "fill and draw" operations immediately after the commissioning of the reservoir. We further consider that any continuing salinity due to the leaching of salt from the bed material would be at a low and ever-reducing level.

(c) Contamination from the sea

With the type of barrage proposed, seepage of sea water into the reservoir would be negligible. The structure would have a freeboard margin on the seaward side above the highest wave level. The spillway, fish pass and other outlet arrangements would be designed to prevent reverse flows of sea water, while there would be no navigational locks to act as possible intermittent inlets. In these circumstances the only contamination of the reservoir from the sea would be by spray or air-borne spume carried over the top of the barrage by strong winds from the west or south-west. Even under gale force conditions the quantity of salt water entering the reservoir in this way would be small in relation to the quantity of fresh water stored in or flowing through the reservoir. By virtue of the high dilution factor the amount would not in our view be sufficient significantly to raise the chloride content of the water.

(d) Final quality of stored water and required treatment

Because of the limited storage capacity available in the reservoir in relation to the size of the catchment area, the physical and chemical characteristics

of the stored water would be subject to fairly wide variations over the range from dry weather to wet weather conditions. Storage in itself, however, could be counted on to improve the bacteriological condition of the water at all times, having regard to the fact that in dry weather when the diluting influence of the river flows would be lowest, the retention period in the reservoir would be longest.

By acting as a settling basin the reservoir would also play a useful rôle in reducing turbidity, which could be particularly marked at the east end when the Eden and Esk were in flood or when wave action stirred up bottom sediment from the extensive shallows there. With the abstraction point located alongside the barrage at least 5 miles (8 km) to the west, we would expect any residual turbidity to be of a low order, even in the event of a summer storm occurring when the reservoir level was drawn down.

It is evident that the widest variations would apply to the colour of the stored water which, on the limited information at present available, would possibly range from 20° - 50° Hazen in dry weather to perhaps 70° - 100° Hazen or more after heavy rainfall. A fuller sampling programme would provide more positive information on this subject.

The stored water would be moderately soft and of neutral or slightly alkaline reaction. For general domestic use it would not require softening, but would have to be clarified and purified. For this purpose we consider that it would respond to treatment by the conventional methods employed for the majority of the impounded surface water sources in this country, based on chemical coagulation, pre-settlement, rapid sand filtration, pH correction and finally disinfection. In this process the presence of turbidity or high colour would not pose any special problems, although the chemical dosages required would rise in sympathy with the colour of the raw water. By such treatment potable water of good quality could be produced.

Having regard to the scale of the works it would be of advantage, if time were available within the construction programme, to base the detailed design of the treatment provisions and the choice of chemical coagulant best suited to the conditions on pilot plant trials carried out over a period following the commissioning of the reservoir.

If, as has been tentatively mentioned, the reservoir were used as a source of supply for river regulation schemes, the physical, chemical and bacteriological condition of the water supplied would require to be no worse than that obtaining at each particular point of time in the rivers receiving the augmentation flows. When there was widespread precipitation causing heavy run-off, conditions on the rivers would in all probability be at least similar to those in the reservoir. At such times the quantity of water supplied would normally be at a minimum. The maximum rate of delivery would occur in dry periods when the quality of the stored water would be at its best. In these circumstances it would meantime appear that water utilised for river regulation purposes could be delivered from the reservoir untreated, and that this could be done without risk of serious problems arising in the aqueducts through the development of growths or deposits.

III. WORKS AND COSTS

Barrage dimensions

At the barrage site the distance across the firth between high water marks is 6600 feet (2010 m). Projecting from both shores are the embankments which formed the approaches to the old railway viaduct. Constructed about 100 years ago of boulder clay protected on the side slopes by heavy blocks of squared sandstone, these embankments are still in good condition and can accordingly be incorporated in the shore ends of the barrage. The net width across the firth between the embankments is 5700 feet (1740 m).

To ensure the exclusion of sea water under extreme conditions, the cope level of the wave or spray wall surmounting the barrage structure would be at a minimum of + 35 feet (10.67 m) O.D. This is based on the tidal surge level of + 22.4 feet (6.83 m) O.D. previously noted for the barrage site, with the addition of (1) an allowance of 1.5 feet (0.46 m) in respect of a continuing rise in sea level in accordance with the long-term trend, (2) a figure of 6.7 feet (2.04 m) for the estimated maximum height of wave liable to occur in a 50-year storm, and (3) a freeboard margin of 4.4 feet (1.34 m) for wave energy dissipation.

On the line of the barrage the surface of the sea bed varies in level from + 3 feet (0.91 m) to - 14 feet (4.27 m) O.D., and the height of the structure would range from 28 feet (8.5 m) to 48 feet (14.6 m).

The line of the barrage would coincide exactly with that of the former railway viaduct, with the base of the structure straddling the old piled foundations of the bridge piers. The suggested alignment and a profile of the estuary at the site are shown on Plan No. 4.

Ground and tidal conditions

There are indications that the fine-grained sand forming the sea bed at the site is in relatively shallow layers overlying boulder clay of no doubt similar nature to that outcropping at several places along the Solway shores. Within or below the beds of boulder clay there may be pockets or lenses of gravel, the whole overlying shale or sandstone rock. A bore put down near Bowness in 1809 indicated rock at 40 feet (12.2 m) below the surface. The available drawings of the old railway viaduct unfortunately do not give precise foundation details, but the piers were apparently founded on piles driven into the boulder clay below the surface sand.

The lack of positive information on the strata and their properties makes it difficult to assess accurately the most suitable type of barrage construction. For present purposes we have looked into several different preliminary designs from which the final choice would depend on the results of exploratory borings, soil

mechanics investigations and a detailed appraisal of economic and site circumstances.

At the barrage site more than half the line dries out at low tide, when there is a low water "stand" of several hours' duration. When the tide is running there are strong tidal streams particularly on the flood at springs. These conditions rule out the use of floating plant for constructional purposes.

Method of closure

Barrages or sea dykes which have been constructed in other countries, especially the Netherlands, are generally of considerable length. The normal procedure in these circumstances is to extend the structures out from both coasts towards an ever-narrowing gap, which is eventually sealed usually by sinking caissons of special design.

For the conditions on the Solway, where the barrage is short and where the tidal velocities are high from the outset, we consider from our preliminary assessments that closure might best be effected in the vertical rather than in the horizontal direction. To this end the barrage would be formed of non-erodible material and built up in longitudinal layers so that, while partially constructed, it would act as a long broad-crested weir for the passage of tidal flows in either direction. An important advantage to be gained from this method is that as construction proceeded more and more water could be impounded behind the barrage, thereby progressively reducing the total volume of water to be passed outwards or inwards on each tide.

Preliminary calculations of the changes of velocity likely to occur during gradual closure as described indicate that with the structure brought up to a level of about + 12 feet (3.66 m) O.D. the velocity would be in the region of 18 feet per second (5.5 m/s) thereafter diminishing as the height of the structure increased.

Spillway provisions

In our view the most effective method of flood discharge and control would be by means of a battery of syphons, 100 in number, each capable of discharging up to 1800 cusecs (51 m^3/s) or an average of 1400 cusecs (40 m^3/s) during the most adverse tidal cycle occurring when the highest astronomical tide is accompanied by tidal surge. By comparison with alternative types of installation, an advantage of the syphonic system is that it obviates the need for large steel gates which, with their fairly elaborate operating headgear and attendant moving parts, could give rise to maintenance problems on this exposed estuarial site.

The battery of syphons would be contained in a block, 1450 feet (442 m) long, forming part of the barrage structure and located as shown on Plan No. 4. The syphons would be positioned at a low level and could therefore be used for scouring and emptying purposes in addition to their main function of dealing with flood discharge. In addition to the syphons a bottom sluice would be incorporated at the lowest possible level.

The syphon valves would be connected by pipes to vacuum pumps situated in

the pumphouse adjacent to the syphon block. Duplicate plant would be provided, including standby diesel generators against the contingency of electrical power failure. Stoplog arrangements would be incorporated so that individual syphons could be isolated for inspection and maintenance. The final form of the preliminary syphon arrangement shown as Fig. E on Plan No. 6 would be determined after comprehensive hydraulic model studies.

As the spillway provisions would require to be in commission in advance of the closing of the barrage, the syphon block would occupy an early place in the construction programme. It would be formed of concrete and built "in the dry" within a cofferdam of steel sheet piling. Transverse joints designed to accommodate possible differential settlement would be provided at intervals along the length of the block.

Fish passes

For present purposes we have based on the provision of twin fish passes located at the north end of the syphon block, which is near mid-firth and remote from the site proposed for the draw-off works within the reservoir. These passes would act as controlled "lifts" and would comprise chambers interposed between the sea on the one side and the reservoir on the other. The inlets and outlets would be a series of valved ports arranged at stepped heights to allow for the variations of water level on each side. These ports would be operated to ensure that, for example, fish travelling upstream could always swim against a current of fresh water, for which purpose the fresh water level within the chambers would have to be raised or lowered by pumping, particularly at times of high tide.

Such fish passes could be designed to incorporate traps as well as instrumentation for recording the runs of fish, complete with tagging facilities for research, control and management purposes.

Barrage design

The syphon block divides the barrage proper into two sections, one 3250 feet (990 m) long to the north, and the other 1000 feet (305 m) long to the south of the block. For these stretches we have considered four different possible designs of barrier, two based on rock and sand fill embankments, and two based on concrete structures.

To facilitate the use of land-based plant, and to permit operations to proceed at virtually all states of the tide, it would be of advantage to provide alongside the line of the barrage a bridge either of temporary or permanent construction primarily to act as a working platform. The bridge could be designed to become part of the barrage structure, thereby providing road access to the control equipment on the barrage as well as serving as a road link across the firth.

All schemes accordingly would incorporate a 24-feet (7.3 m) carriageway road which would be at level + 31 feet (9.45 m) O.D. rising to + 34 feet (10.36 m) O.D. over the syphon block. These levels would suit the height of the existing

shore embankments. The road would therefore be a minimum of 10 feet (3.05 m) above the possible ultimate water level in the reservoir and would be protected on the seaward side by the 4-feet (1.22 m) high wave wall at a minimum level of + 35 feet (10.67 m) O.D. The approaches would be linked to the Trunk Road A.75 near Annan on the Scottish side and to the unclassified coastal road at a point west of Bowness on the English side.

Our investigations indicate that there are sandstone quarries within a few miles of Annan and that granite for face protection work is obtainable from Criffell some 20 miles (32 km) to the west. Stone quarries are also found to the south of Carlisle. There are large quantities of blast furnace slag and colliery waste in the Maryport area which, if free from toxic material, could be used for general filling. Gravel aggregates and sand for concreting purposes are available from pits in the Longtown district about 11 miles (18 km) from Annan. A more detailed survey may reveal sources of rock, gravel and sand in closer proximity to the site.

Embankment construction

Fig. A on Plan No. 5 shows a suggested design for an embankment. Heavy rock fill would be placed to form a seaward barrier which would be gradually extended in shallow layers and raised to a level of about + 22 feet (6.71 m) O.D. until closure of the sections on both sides of the syphon block was achieved. Thereafter, in the relatively quiescent water behind this rock barrier, another rock toe would be formed on the upstream side. Selected sand filling would then be placed between the two rock mounds and contained by means of the graded filter layers on the inner slopes.

An impermeable diaphragm could be formed either by driving steel sheet piling through the sand zone into the boulder clay foundation or by constructing a reinforced concrete diaphragm wall in the same location by the bentonite displacement trench method. After raising to level the roadway and wave wall would be formed on the top of the embankment.

To permit the early and independent construction of the syphon block a temporary bridge giving access to that unit would have to be provided from the south shore. For the formation of the embankment it is anticipated that the closure mound would be constructed by end tipping for as great a distance from the north shore as tidal conditions would allow. To enable the final closure to be formed in horizontal layers, the temporary bridge to the syphon block would require to be extended across the remaining gap.

In view of the advantages of giving early access over the whole length of the barrage we prepared an alternative design based on the provision of a simple piled bridge of permanent construction extending across the firth. Fig. B shows a modified embankment constructed round such a bridge, again incorporating an impermeable diaphragm. This scheme entails the construction of the seaward rockfill barrier similar to Fig. A, but in this case it is suggested that the top section of the barrier be trimmed after construction of the diaphragm to form the final slope of the embankment, thereby conserving rock fill. Under this arrangement about 25% less fill material is required than with the other embankment scheme.

Concrete construction

Figs. C and D on Plan No. 6 show possible alternative forms of concrete structure, which obviously require less volume of material than the embankment types. The design indicated in Fig. C visualises the construction of a bridge across the Solway as the first stage with the formation of the concrete barrier following on behind. It is assumed that the barrier could be raised in lifts to certain defined levels to suit the "long weir" type of closure, and either precast facing planks or suitable temporary shuttering could be adopted.

The type of structure shown in Fig. D would be constructed from a temporary bridge. In this case heavy travelling shutters could be suspended from a temporary gantry and deep pours of concrete obtained, which would mean combining to some extent the "long weir" and "gap" forms of closure.

Both types of concrete structure could be built without the need for conventional cofferdams but steel sheet piling would be driven well into the boulder clay to provide protection against scour at both the seaward and the landward toes. By containing the foundation material within the sheet piling some improvement in bearing pressure conditions could be expected. If such concrete structures were founded in boulder clay, some differential settlement would probably be experienced and suitable joints would have to be incorporated to allow for relative movement between sections of the barrier.

On present information the four types of construction described appear to lie generally within the same range of cost, with the concrete structures tending towards the upper end of the scale. A closer analysis could alter the position depending on the outcome of further investigations, but meantime for the purposes of probable cost in this report the higher range has been adopted. As the barrage is only 1.25 miles (2.0 km) long and less than 40 feet (12.2 m) in average height the cost of its construction is not the major factor in the overall expenditure involved in making potable water available from the Solway.

Draw-off works

The intake works, located alongside the barrage near the south end of the syphon block, as shown on Plan No. 4, would be enclosed by mechanically raked trash screens through which the water would pass to the pump suctions. For abstraction, we visualise a series of pumps delivering the water directly from the reservoir to the treatment works, which we suggest be located on the English side in the area immediately to the south of the coastal road near Bowness, as indicated on Plan No. 2.

The pumphouse superstructure, embodying an electrical substation, would house the pump motors, starters, switchgear, and associated equipment. Both the substructure and the superstructure of the pumphouse would be planned so that the initial provisions could be extended in stages to an ultimate capacity of 585 mgd (30.8 m^3/s) according to the trend of future demands.

The low-head abstraction pumps would deliver the water to the inlet of the treatment works at about + 50 feet (15.24 m) O.D. Over the distance of about

half a mile (0.8 km) the delivery mains would be formed of 72-inch (1.83 m) diameter pipes, eventually six in number, each having a capacity of about 100 mgd ($5.26\ m^3/s$). These could be laid in units to match the capacity requirements from time to time.

Treatment works

The treatment works would also be designed for construction on the unit principle to permit ready extension as required. There would be main building blocks for administration and control and for chemical storage. Other principal items would be the extensive groups of pre-settlement tanks and of rapid gravity filter beds, from which the filtered water after pH correction and disinfection would be delivered to clear water storage tanks having a top water level at about + 35 feet (10.67 m) O.D. These tanks, with a capacity for balancing purposes equivalent to 3 hours' retention on the station throughput, would be the take-off point for the high-head pumps required for the distribution of the supply. In addition to the requisite access and connecting roads the provisions would include houses for the station attendants.

In line with modern practice the station would incorporate mechanical equipment for the bulk-handling of chemicals and electrical equipment for the automatic control of chemical dosing and filter washing. For present purposes we have assumed that it would be permissible to discharge the sludge from the pre-settlement tanks and the wash water from the filters to the Solway on the downstream side of the barrage, thereby obviating the need for sludge separation and disposal works.

Dredging

An appropriate size of cutter-suction dredge for use in the reservoir would be a vessel perhaps up to 150 feet (45.7 m) long with 40 feet (12.2 m) beam and 6 feet (1.8 m) draught, fitted with 16-inch (0.4 m) bore suction and delivery pipelines. Such a vessel, which could be transported in sections by land for assembly and launching into the reservoir at a selected point on the shoreline, would have a potential output capacity of the order of 3 million cubic yards ($2.29 \times 10^6 m^3$) per annum. If improvement dredging were combined with maintenance dredging, an installation of this type could be kept in continuous operation for 20 to 25 years.

While the Water Authority having control of the source might elect to provide and operate their own dredging plant, for present purposes we have based on the work being carried out by a dredging firm under long-term contract. By the time it became necessary to undertake dredging, the scheme would be revenue producing and it would seem appropriate accordingly to express the dredging costs as annual charges both in respect of the improvement and the maintenance elements.

Our enquiries indicate that for the installation and eventual removal of the dredging plant, with its value wholly written off over the contract period, and including comprehensively for fuel and other consumable stores, for labour, for plant maintenance, repairs and renewals, and for control at the reclamation areas, the cost of removing 3 million cubic yards ($2.29 \times 10^6 m^3$) yearly would amount to £450 000 per annum if Rockcliffe and Burgh Marshes were used as the spoil grounds, or £750 000 per annum if the dredged material had to be conveyed over the longer

distance to the estuary of the Wampool and the Waver. These costs, which are equivalent to unit rates of 3/- and 5/- per cubic yard (4/- and 6/6 per m^3), show that there would be considerable economic advantage in using Rockcliffe and Burgh Marshes as the disposal grounds. As this would fit in with the ultimate third stage of the scheme we have meantime based accordingly.

It may be observed that if on completion of the improvement dredging the reservoir impounding level were raised as suggested to + 21 feet (6.40 m) O.D., the silting up period of the reservoir would be extended to about 700 years. In these circumstances there could be longer intervals of time between future operations for maintenance dredging.

Under the first stage of development the net yield will be subject to gradual reduction due to siltation in the reservoir. In calculating the unit cost of the water we have allowed for this factor by assuming that, pending the execution of dredging, there would be allocated from revenue to say a reserve fund for maintenance dredging an annual sum of £60 000, which is the cost of removing the estimated annual amount of siltation at the 3/- per cubic yard (4/- per m^3) rate.

Full feasibility study

To complete a feasibility study of the Solway Barrage scheme the information provided by the present desk study would require to be supplemented by detailed investigations based on aerial and hydrographic surveys, on exploratory borings and on tidal and hydraulic models. Particulars of the requirements for the full study are listed as an appendix in Table No. 6, together with details of the estimated cost of £300 000.

Development period

The programme of investigations included in the comprehensive feasibility study would occupy a period of 2½ to 3 years. If the outcome of that study were satisfactory, progress thereafter would depend on several important policy considerations, involving in particular decisions on the use to be made of the source and on the form of authority to be responsible for constructing and controlling the barrage, together with the negotiation of the detailed financial arrangements and the acquisition of the necessary statutory powers. A time interval of 3 years would possibly be taken up by this consultation and promotion stage. After authorisation, a period of 1½ to 2 years would be required for the preparation of detailed designs, working drawings and contract documents following which the works could be built and commissioned within a construction period of 4 years. On this basis it would appear that from the start of the feasibility study a total period of 11 to 12 years would be required to make water for supply available from the scheme.

Estimates of Cost

The estimates of capital cost are based on current (1966) rates and are inclusive of contractor's general items, engineering, site supervision and a contingency allowance which we have pitched rather higher than usual because of the limited information meantime available in regard to site conditions. Allowance is made for interest during construction (at 7% over 4 years) but not for land or legal charges.

Annual costs are calculated on loan periods of 60 years for heavy civil engineering works, 40 years for buildings and 20 years for mechanical and electrical plant, with interest at 7%. Allowances are made for the operation and maintenance of the works, but not for administration, depreciation, insurances or local rates.

Capital Costs

For the first stage of development the estimated capital costs are as under:-

	Capital Costs (£ million)			
	For full yield of 380 mgd ($20.0\ m^3/s$)		For initial supply of 100 mgd ($5.26\ m^3/s$)	
Full Feasibility Study		0.3		0.3
Barrage Works (including roadway)				
Spillway block	2.25		2.25	
Linking barriers	2.35		2.35	
Approaches	0.30		0.30	
Syphon and fish pass equipment	0.30		0.30	
Interest during construction	0.80	6.0	0.80	6.0
Draw-Off Works				
Intake & pumphouse substructure	0.60		0.25	
Pumphouse superstructure	0.13		0.05	
Pumps, screens and other plant	0.40		0.20	
Pipelines to treatment works	0.35		0.11	
Interest during construction	0.22	1.7	0.09	0.7
Treatment Works				
Tanks and foundations	11.00		3.10	
Buildings	1.80		0.60	
Plant and equipment	5.45		1.50	
Interest during construction	2.75	21.0	0.80	6.0
Totals		£ 29.0 million		£ 13.0 million

Extension of the draw-off and treatment works to deal with the additional yield produced hy the second stage of development would involve extra expenditure of £5.0 million. Similar extensions to match the third stage yield, including for the land drainage and road protection works then required, would add a further sum of £8.0 million to the cost.

The overall capital costs of the several stages of development may be summarised as under:-

	Capital Cost
For the first stage, with the treatment works limited to an initial capacity of 100 mgd (5.26 m^3/s)	£13 million
For the first stage, fully developed to produce 380 mgd (20.0 m^3/s)	£29 million
For the second stage, fully developed to produce 465 mgd (24.5 m^3/s)	£34 million
For the third stage, fully developed to produce 585 mgd (30.8 m^3/s)	£42 million

Annual Costs

For the first stage of development the annual charges and the unit costs of the water wculd be:-

	Annual Cost for full supply of 380 mgd (20.0 m^3/s)	Unit Cost Pence per 1000 gallons	Unit Cost Pence per cubic metre
Loan charges			
Full feasibility study	22 000	0.04	0.01
Barrage works	434 000	0.75	0.17
Draw-off works	131 000	0.23	0.05
Treatment works	1 630 000	2.82	0.62
Operation and Maintenance charges			
Electrical power for pumping and treatment	230 000	0.40	0.09
Chemicals for treatment	380 000	0.66	0.14
Lahour for attendance at barrage, draw-off and treatment works	53 000	0.09	0.02
Maintenance of works, including consumable stores, repairs and replacements	115 000	0.20	0.04
Charge to reserve fund for maintenance dredging	60 000	0.10	0.02
Totals	£3 055 000	5.29d	1.16d

With the draw-off and treatment works limited in the first instance to a capacity of 100 mgd (5.26 m^3/s), the unit cost of providing 100 mgd of treated water would he 8.35d per 1000 gallons (1.84d per m^3).

The unit cost of untreated water delivered to tanks at the + 50 feet (15.2 m) O.D. level would he 1.62d per 1000 gallons (0.36d per m^3) for the full supply of 380 mgd (20.0 m^3/s) and 4.40d per 1000 gallons (0.97d per m^3) for the first 100 mgd (5.26 m^3/s).

The second stage of development would hring the net yield of the source to 465 mgd (24.5 m^3/s) at an extra cost of £5 million, which would create additional loan charges of £385 000 per annum. By that time some of the loans in respect of the first stage works might well have been paid off, hut discounting that possibility, and adding in a charge of £450 000 per annum for improvement dredging in place of the charge of £60 000 per annum for maintenance dredging, the unit cost of treated water comes out at 5.65d per 1000 gallons (1.24d per m^3). This would fall to 5.10d per 1000 gallons (1.12d per m^3) on completion of the improvement dredging.

The third stage of development would further increase the yield to 585 mgd (30.8 m^3/s) at an extra cost of £8 milllon which would create additional loan charges of £618 000 per annum. On the same hasis as hefore, this would result in a unit cost for treated water of 5.00d per 1000 gallons (1.10d per m^3).

The unit costs for treated water provided in tanks at the + 35 feet (10.67 m) O.D. level under the several stages of development may he summarised as under:-

		Unit Cost	
		per 1000 gallons	per cubic metre
For the first stage, with the treatment works limited to an initial capacity of 100 mgd (5.26 m^3/s)	.....	8.35d	1.84d
For the first stage, fully developed to supply 380 mgd (20.0 m^3/s)	.....	5.29d	1.16d
For the second stage, fully developed to supply 465 mgd (24.5 m^3/s)	.....	5.65d	1.24d
For the second stage, after completion of the improvement dredging	.....	5.10d	1.12d
For the third stage, fully developed to supply 585 mgd (30.8 m^3/s)	.....	5.00d	1.10d

The unit costs for hoth treated and untreated water over the whole range of supply are shown graphically on Diagram No. 5. The stepped-up parts of the curves coinciding with the second stage of development indicate the effect of undertaking the improvement dredging.

IV. GENERAL OBSERVATIONS

Fisheries

The Solway Firth and the rivers entering it are important from the fishery aspect particularly as regards migratory fish. The Eden is a popular salmon river on which the rod fisheries take about 1600 per annum. The Esk is well known for its runs of sea trout. Coastal fisheries for salmon, grilse and sea trout are operated on a commercial basis along the shorelines both above and below the barrage site. Along the English shore haaf-net fishing is practised but on the Scottish side the method of catch is mainly by fixed stake nets, which are illegal on the opposite shore. The Scottish stake nets take an annual catch of the order of 18 000 salmon and grilse and 20 000 sea trout.

The construction of a barrage would substantially alter the present regime in the estuary. It may be assumed that both the river and the coastal fishings would be adversely affected by its introduction but informed opinion suggests that the fish would in time adapt themselves to the changed environment. Although there is a recognised dearth of precise knowledge about the habits and requirements of migratory fish, we are advised that by providing an adequate fish pass and a sufficient flow of fresh water to attract fish to it, the important salmon and sea trout fisheries of the rivers entering the Solway above the barrage could be maintained, although it could not at present be ensured that the runs of fish would retain the same patterns of timing and numbers as they now show. Problems requiring special attention might arise in connection with the passage of smolts from the rivers to the sea and also through the presence of pike or other predators in the reservoir. On the other hand the reservoir as a freshwater lake, apart from its attractions as an amenity, could become a valuable asset not only for trout fishing but also for yachting and other controlled recreational activities.

Navigation

There are no ports upstream of the barrage line but about a mile (1.6 km) downstream on the Scottish side is the small harbour at Annan to which access is by the river channel at times of high water. The harbour dries out completely at low tide. Shipping traffic is light in amount and limited to vessels of small size, although the river channel is also used for towing away large boilers launched from the slipway of a local factory. The approaches to Annan harbour would not be directly affected by the construction of a barrage, but indirect effects might arise through changes in the pattern of the present tidal streams at the mouth of the River Annan. The nature and extent of any such effects could only be determined in advance by means of a mobile-bed tidal model.

Silloth, situated 9 miles (14.5 km) downstream on the English coast, is a port of considerable local importance handling cargo of about 100 000 tons (101.6×10^6 kg) per annum, the bulk of which goes to the flour mills situated

alongside the inner dock. The harbour here is subject to siltation problems and it has been represented to us that the construction of a barrage would, by reducing the flood run-off from the rivers, aggravate existing conditions at Silloth and probably lead to the complete silting up of the navigable channel to the port. Ae the reservoir will trap much of the silt now carried down-firth, and as by the flood control arrangements the peak discharges on the ebb tide could be greater than at present, we consider that the overall effect is unlikely to be serious. This is again a matter, however, which would require investigation by means of a mobile-bed tidal model.

Road communications

The provision of a road link across the Solway Firth at the barrage would be likely to generate considerable traffic. We are informed that much of the output from the flour mills at Silloth is distributed to Dumfries and beyond, and we aleo understand that the pulp mill now under construction near Workington will draw a considerable part of its timber requirements from South-West Scotland. In addition to theee particular examples there are indications that much of the general traffic passing between Scotland and the Cumberland coast would be attracted to a crossing near Annan. A traffic origin and destination census baeed on selected points on both sides of the border would provide useful information on this subject.

If there were such a build-up of traffic it would be desirable to provide a new 24-feet (7.3 m) road extending southwards from the barrage over the distance of about 9 miles (14.5 km) to a junction with the existing Trunk Road A.596 near Wigton, as indicated on Plan No. 7, which shows the present road pattern in the area.

These proposals refer to a single two-lane carriageway, as is incorporated in the preliminary barrage designs. The layout of these works would be planned to allow for the future duplication of the road to provide a dual carriageway highway, and the same would advisedly apply to the suggested link road between the barrage and Wigton.

Alternative barrage sites

The alternative barrage site to which we have given most attention is that on a line between Barnkirk and North Plain, about a mile (1.6 km) downstream of the viaduct line. A barrage here would be about one-third longer and would have a contributory catchment increased by 374 square miles (970 km^2) by the inclusion of the River Annan.

As the capacity of the reservoir basin would not be increased in proportion to the size of the additional catchment, the resulting gain in effective yield would be relatively small and also fairly expensive because of the extra cost of the barrage works. Moreover, the flood diecharges from the Annan and the high silt burden which it carries in times of spate would aggravate the problems of flood control and siltation and lead to high turbidity in the reservoir in the immediate vicinity of the draw-off works. For these reasons we consider that the viaduct line is to be preferred.

The other three possible sites we have considered would involve barrages from 5 to 8 miles (8 to 13 km) in length. These could produce yields for water supply purposes up to 2000 mgd (105 m^3/s) or more but the scale and cost of the barrage works required would rise at a proportionately greater rate than would the extra yields obtainable. In particular the closure problem would become increasingly magnified as the area of the enclosed tidal basin was extended. In the case of the outermost line between Southerness Point and Dubmill Point, provision would have to be made for the maintenance of shipping traffic to Silloth. Also, because of the greater exposure of the barrage to the open sea on this site wave heights would be much greater than for a short barrage in the more sheltered inner estuary. Allowing for the maximum height of wave liable to occur in a 50-year storm, the top of the wave wall surmounting a barrage on the outermost line would require to be at +45 feet (13.72 m) O.D., or 10 feet (3.05 m) higher than applies at the selected site.

It would meantime appear that these other possible barrage sites would only merit further and more detailed examination in the event of there arising prospective demands for water in excess of the supply of 585 mgd (30.8 m^3/s) made available by the scheme outlined in this report.

V. ACKNOWLEDGMENTS

In addition to the deliberations at the meetings of the Steering Committee held during the course of our investigation, we have had the benefit of on-the-spot discussions with Mr. J.W. Shiell of the Scottish Development Department and Mr. A.G. McLellan of the Water Resources Board during a tour of the Solway area. We have also had useful exchanges of view on matters of common interest with Sir Alexander Gibb and Partners, arising out of their concurrent investigations into the Morecambe Bay Barrage scheme.

We are particularly indebted to the following parties for their assistance as specialist advisers, as sources of documentary and other records or as contributors of individual views.

Specialist Advisers	Subject
1. Meteorological Office.	Rainfall and evaporation data.
2. University of Strathclyde, per Professor W. Frazer, Department of Civil Engineering.	Advice and assistance in the establishment and observation of temporary tide gauges.
3. Hydrographer of the Navy, per Commander D.L. Gordon, Superintendent of Tidal Branch.	Calculation of tidal levels from survey information supplied.

4. University of Liverpool Tidal Institute, per Dr. J.R. Rossiter.	Calculation of tidal levels and surge heights from survey information supplied.
5. Mr. L. Draper, of the National Institute of Oceanography.	Wave height investigations.
6. Mr. F.T.K. Pentelow.	General advice on river and coastal fisheries.
7. Dr. E.A.B. Birse, Chief Chemical Inspector, Scottish Development Department.	Information and advice on radio-activity in the Solway.
8. Institute of Geological Sciences, Edinburgh and Leeds Offices.	Information on the general geology of the Solway area.
9. The Nature Conservancy, per Mr. T. Huxley, Edinburgh.	Information on Nature Conservancy's interests in the Solway area.
<u>Sources of documentary records</u>	<u>Subject</u>
10. Ordnance Survey.	Maps and aerial photographs.
11. Hydrographer of the Navy.	Copies of old Admiralty Charts.
12. Department of Agriculture and Fisheries for Scotland, per Mr. J.K.C. Wilson.	River gauging records for the Nith and the Annan.
13. The Solway River Purification Board, per Mr. C.P. James, River Inspector.	Records of river gaugings and water analyses, information on effluents and programme of suspended solids sampling on the Esk.
14. The Cumberland River Authority, per Mr. A.J. Collins, Chief Engineer.	Records of river gaugings for the Esk and the Eden and water analyses for the Eden, with information on effluents and on land drainage.
15. British Rail, per the Chief Civil Engineer's Department, Scottish Region.	Plans of the old railway viaduct across the Solway.
16. Files of "The Glasgow Herald" .	Report on the collapse of the Solway viaduct, 1881.
17. Paper by Dr. H.L. Penman in the Journal of the Royal Meteorological Society, 1950, reprinted in the Journal of the Institution of Water Engineers, August 1954.	"Evaporation over the British Isles" .

18.	Report by the Institution Research Subcommittee on Rainfall and Run-off, in the Proceedings of the Institution of Civil Engineers, February 1960.	"Floods in the British Isles".
19.	Paper by Mr. G.W. Lennon in the Proceedings of the Institution of Civil Engineers, August 1963.	"A frequency investigation of abnormally high tidal levels at certain west coast ports".
20.	Paper by Mr. G.O. Lockwood in the Proceedings of the Institution of Civil Engineers, February 1953.	"Sea defence works at Silloth, Cumberland".
21.	J.R. Marshall (Dr. Joan Rees), 1961, Ph.D. Thesis (unpublished), "Investigations into some aspects of the physiography of the Upper Solway Marshes and Mosses".	An exhaustive treatise providing much useful information on the physical, geological, climatic and other features of the Solway.
22.	J.B. Wilson, 1965, Ph.D. Thesis (unpublished). "The paelaeoecological significance of infaunas and their associated sediments".	Data on the sediments of the Solway.
23.	United Kingdom Atomic Energy Authority, per Dr. C.J. Porter, Chapelcross, Annan.	Information on investigations into effluent discharge to the Solway, with aerial photographs.
24.	United Kingdom Atomic Energy Authority, Production Group Reports by E.J. Perkins, M. Bailey and B.R.M. Williams.	"The biology of the Solway Firth in relation to the movement and accumulation of radio-active materials".
25.	Dr. E.J. Perkins.	"Some preliminary notes on the bottom currents of the Solway Firth and the N.E. Irish Sea".
26.	Paper by Mr. H.C. Gilson of the Freshwater Biological Association presented at the Symposium on Man-made Lakes, arranged by the Institute of Biology, 30th November, 1965.	"The biological implications of the proposed barrages across Morecambe Bay and the Solway Firth".
27.	Captain R.J. Nicholls, Harbour Master, Silloth.	Information on shipping traffic to Silloth, tidal data and facilities for installation of additional tide gauge.
28.	Mr. T. Willacy, Harbour Master, Annan.	Information on shipping traffic to Annan.

29. Report of Lord Hunter's Committee. H.M.S.O., August 1965, Cmnd. 2691. — "Scottish Salmon and Trout Fisheries".

Contributors of individual views

30. Mr. P. Liddell, Chairman, and Members of (a) the Northern Committee of the Salmon and Trout Association, (b) the Fisheries Committee of the Cumberland River Authority, and (c) the River Eden and District Fisheries Association. — Views on the possible effects of a barrage on the river fishings.

31. Mr. F. Ivan Carr, Managing Director of Carr's Flour Mills, Carlisle and Silloth. — Views on the possible effects of a barrage on navigation to the Port of Silloth.

Babtie Shaw & Morton

95 BOTHWELL STREET,
GLASGOW, C.2.

22nd July, 1966.

TABLE NO. 1

TIDAL LEVELS

Place	Lowest Astronomical Tide	Mean Low Water Springs	Mean Low Water Neaps	Mean High Water Neaps	Mean High Water Springs	Highest Astronomical Tide
	feet	feet	feet	feet	feet	feet
Silloth	- 15.5	- 11.7	- 6.7	+ 8.2	+ 15.8	+ 18.9
Newbie	- 6.9*	- 6.9*	- 6.2	+ 8.7	+ 16.4	+ 19.6
Glasson	+ 0.8*	+ 0.8*	+ 0.8*	+ 9.0	+ 17.7	+ 21.2
Redkirk	+ 5.6*	+ 5.6*	+ 5.6*	+ 9.6	+ 18.1	+ 21.7
	metres	metres	metres	metres	metres	metres
Silloth	- 4.72	- 3.57	- 2.04	+ 2.50	+ 4.82	+ 5.76
Newbie	- 2.10*	- 2.10*	- 1.89	+ 2.65	+ 5.00	+ 5.97
Glasson	+ 0.24*	+ 0.24*	+ 0.24*	+ 2.74	+ 5.40	+ 6.46
Redkirk	+ 1.89*	+ 1.89*	+ 1.89*	+ 2.93	+ 5.52	+ 6.61

*Low river level

RIVER EDEN WATER ANALYSES

Analyses of samples from River Eden below Willowholme, Carlisle, 1964-1965, by Cumberland River Authority

Flow x a.d.f.	Suspended Solids mg/l	Dissolved Solids mg/l	pH	5-day B.O.D. mg/l	Oxygen absorbed in 4 hrs. mg/l	Ammonia as mg/l N.	Nitrates as mg/l N.	Chlorides as mg/l Cl.	Dissolved Oxygen % saturation	Temperature °C.	Alkalinity to methyl orange as mg/l $CaCO_3$	Hardness: Carbonate mg/l	Hardness: Non-Carbonate mg/l
2.7	46		7.2	2.5	9.6	0.11	0.93	28		11.0	90		
1.7	4		7.5	6.0	2.5	0.20	1.02	22		6.0	85		
0.77	10	180	7.3	1.85	3.1	0.00		13	93.8	13.0		90	15
0.7	9		7.4	2.6	2.0	0.52	1.58	25		5.0	125		
0.55	4		7.7	5.2	2.0	0.62	1.38	24	101.7	5.0	120		
0.45	8		5.9	2.9	2.4	0.69	1.88	21	95.9	8.0	130		
0.43	17		5.9	7.5	2.5	0.09	0.82	32	106.4	5.0	110		
0.43	10		7.2	6.0	4.6	0.38	1.50	26			110		
0.40	8		6.9	3.6	2.2	0.32	2.15	19	92.3	16.5	100		
0.38	13		7.1	4.3	2.4	0.38	1.70	24	93.4	12.0	105		
0.33	7		7.6	3.5	3.6	0.42	2.37	19		8.0	130		
0.33	10		7.5	5.0	3.8	0.42	2.64	21	87.7		100		

TABLE NO. 4

RIVER ESK WATER ANALYSES

Analyses of samples from River Esk (over the ten year period 1954-1964) by Solway River Purification Board

	pH		5-day B.O.D. mg/l		Oxygen absorbed in 4 hrs. mg/l		Ammonia as mg/l N.		Nitrates as mg/l N		Chlorides as mg/l Cl		Dissolved Oxygen % saturation		Temperature °C.	
RIVER ESK	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
at Bentpath	8.2	6.9	3.1	0.2	18.2	0.4	0.24	0.01	0.56	0.11	19	7	120.0	86.0	18.0	0.0
at Bridge of Langholm	8.5	6.5	4.1	0.2	21.2	0.4	2.29	0.03	0.70	0.15	22	7	117.5	85.0	18.5	0.0
20 yds. below Langholm sewage works outlet	8.9	6.6	33.0	0.5	21.2	1.2	2.12	0.04	2.70	0.14	45	8	131.0	88.0	19.0	0.0
at Skippers Bridge	8.6	6.9	13.4	0.3	20.0	0.8	0.41	0.05	1.40	0.11	24	8	158.0	87.0	18.0	0.0
at Bridge at Canonbie	8.6	7.1	2.3	0.5	10.8	0.4	0.20	0.04	0.85	0.14	18	8	125.0	91.0	17.0	0.0
at National Boundary	8.7	6.8	5.3	0.3	21.8	0.4	0.18	0.04	1.34	0.10	18	8	138.0	84.0	17.0	0.0

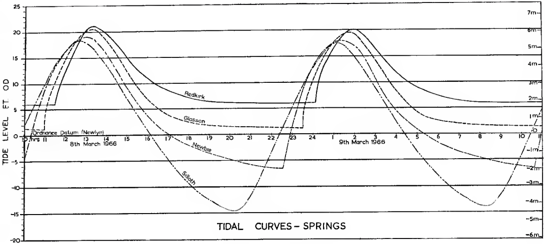
WATER ANALYSES - RIVERS EDEN AND ESK

Analyses by R.R. Tatlock & Thomson, Public Analysts, Glasgow
of samples of water taken on 23rd May, 1966
at approximately 4 x a.d.f.

	River Eden at Carlisle	River Esk at Longtown
	mg/l	mg/l
Mineral Matter in Suspension	110.0	4.0
Organic & Volatile Matter in Suspension....	16.0	1.0
Total Matter in Suspension	126.0	5.0
Carbonate Hardness	65.0	36.0
Non-carbonate Hardness	15.0	8.0
Free Ammonia	0.02	0.01
Albuminoid Ammonia	0.18	0.16
Nitrates as N	0.28	negligible
Free Acidity as CO_2	2.0	2.0
Oxygen absorbed from permanganate in 4 hours at $27^{o}C$	7.0	9.4
Iron in solution	0.24	0.34
Manganese	none	none
Silica	< 1	< 1
Chlorides as Cl	11.0	7.0
Dissolved Solids	130.0	80.0
Turbidity	5	5
Colour (Hazen Standard)	70	100
pH Value	7.2	6.9

ESTIMATED COST OF FEASIBILITY STUDY

Aerial photography and mapping of the coast lines between low water mark and + 50 feet (15.2 m) O.D. seawards to a line across the firth 30 miles (48 km) west of the barrage site	....	£ 20 000
Physical and hydrographic surveys of inner and outer estuaries, comprising echo-sounding, tidal stream tracer work, salinity traverses, temperature and siltation observations, including for the hire, installation and observation of tide gauges and wave recorders throughout the area and of level recorders in ground-water observation wells spaced around the shores of the proposed reservoir	....	55 000
Studies by mobile-bed tidal model covering the whole firth, including lease and adaptation of existing building to accommodate the model, its construction complete with tide generator and instrumentation, and its calibration and operation for a period of say 18 months	....	90 000
Supplementary hydraulic model studies relative to the design of the barrage profile and spillway syphons	....	15 000
Sinking test boreholes from mobile tower rigs to determine foundation conditions at the barrage site and to check the depths of sand deposits within the reservoir basin, including for soil sampling observations	....	35 000
River gauging, water sampling and analyses, with particular reference to bed loads and suspended solids at the higher ranges of flow	....	5 000
Specialist information and advice on rainfall and evaporation, tidal surges, wave heights and fisheries, etc.	....	3 000
Engineering services in co-ordinating the several field surveys and investigations; analysing and interpreting the results of the model and other studies; studying the hydrology of the catchment; determining the usable storage; estimating yields; investigating construction materials; preparing designs and estimates and submitting comprehensive report	....	50 000
		273 000
Contingencies, 10% say	....	27 000
Total	....	£300 000


TIDAL CURVES – SPRINGS
TIDE LEVEL FT. OD
25
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15
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-5
-10
-15
-20
7m
6m
5m
4m
3m
2m
1m
0
-1m
-2m
-3m
-4m
-5m
-6m
Redkirk
Glasson
Newbie
Silloth
Ordnance Datum (Newlyn)
10 hrs 11
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8th March 1966
9th March 1966

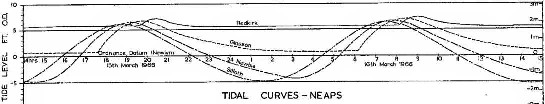
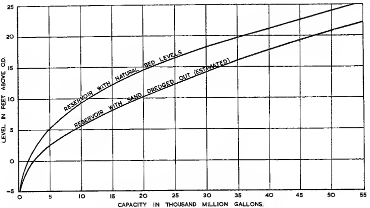
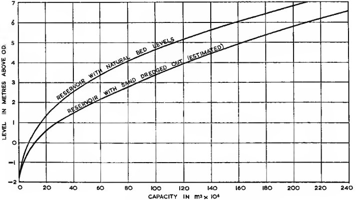

TIDAL CURVES – NEAPS
TIDE LEVEL FT. O.D.
10
5
0
-5
3m
2m
1m
0
-1m
-2m
Redkirk
Glasson
Newbie
Silloth
Ordnance Datum (Newlyn)
14hrs 15
16
17
18
19
20
21
22
23
24
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
15th March 1966
16th March 1966

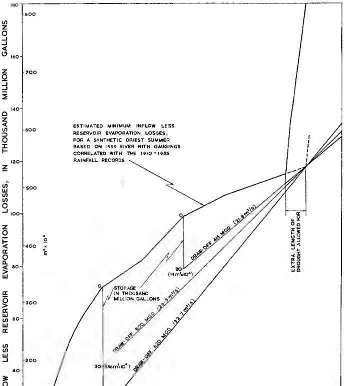
DIAGRAM Nº



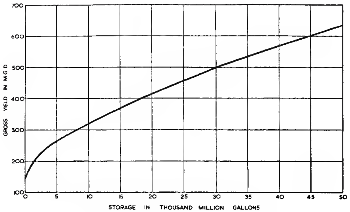
DEPTH-CAPACITY CURVE — BRITISH UNITS.



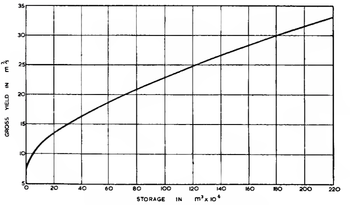
DEPTH-CAPACITY CURVE — METRIC UNITS



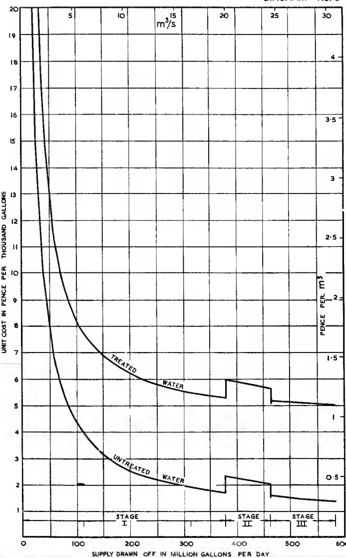
SYNTHETIC CUMULATIVE INFLOW DIAGRAM



YIELD ~ STORAGE CURVE — BRITISH UNITS.

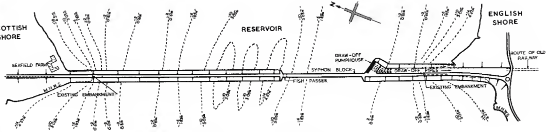


YIELD - STORAGE CURVE — METRIC UNITS

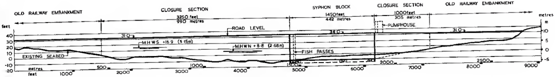


UNIT COST OF WATER

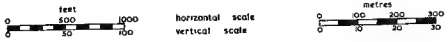
PLAN No. 4.



PLAN OF BARRAGE.



LONGITUDINAL SECTION



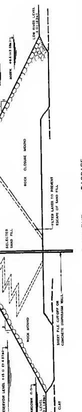


FIG A - EMBANKMENT BARRAGE

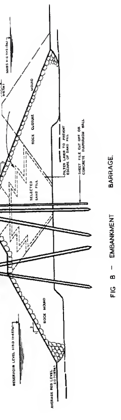


FIG B - EMBANKMENT BARRAGE

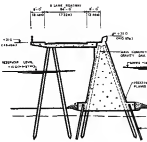


FIG C - CONCRETE BARRAGE

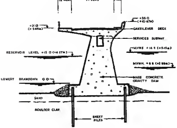
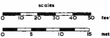


FIG D - CONCRETE BARRAGE



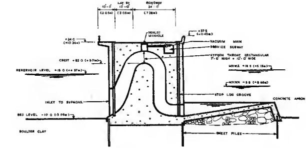
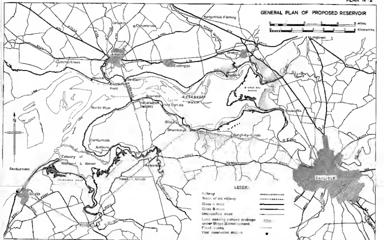
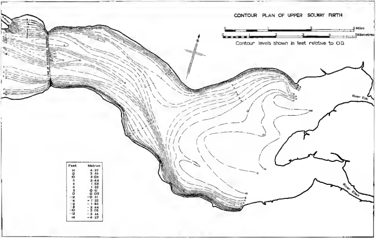


FIG. E - SYPHON BLOCK


GENERAL PLAN OF PROPOSED RESERVOIR
Miles
Kilometres
LEGEND
Railway
Track of old railway
Class A road
Class B road
Unclassified road
Land needing pumped drainage under Stage III development
Flood banks
Tidal observation stations
Kirkpatrick Fleming
Chapelcross
Longtown
ANNAN
Cummertrees
Eastriggs
Gretna
Newbie
Seafield
Bowness
RESERVOIR BASIN
TREATMENT WORKS
Port Carlisle
North Plain
Glasson
Drumburgh
Burgh-by-Sands
Rockcliffe
R. Eden
Cardurnock
Anthorn
Estuary of Wampool & Waver
Kirkbampton
Skinburness
Kirkbride
Newton Arlosh
CARLISLE
Silloth
Abbeytown



Feet	Metres
14	4·27
12	3·66
10	3·05
8	2·44
6	1·83
4	1·22
2	0·61
0	0·00
-2	-0·61
-4	-1·22
-6	-1·83
-8	-2·44
-10	-3·05
-12	-3·66
14	-4·27